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THESIS

THE APPLICATION OF FAULT TREE ANALYSIS
TO AN ANTI-AIRCRAFT WARFARE MODEL

by

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Thesis Advisor: James D. Esary

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(20. ABSTRACT Continued)

when applied to the AAW model is examined with a view toward its usefulness as an instructional and a predictive tool.

The Application of Fault Tree Analysis to an Anti-Aircraft Warfare Model

by

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Submitted in partial fulfillment of the
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ABSTRACT

Fault Tree Analysis is a method implemented through the use of logic symbols, for analyzing either qualitatively or quantitatively the events that lead to a mission or system failure. This work examines an Anti-Aircraft Warfare (AAW) scenario restricted to the defense of an aircraft carrier. A fault tree of the events that lead to a hit on the carrier is displayed logically from the top down. Fault tree analysis when applied to the AAW model is examined with a view toward its usefulness as an instructional and a predictive tool.

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I. INTRODUCTION

A. BACKGROUND

The application of Fault Tree Analysis (FTA) to commercial and military systems has been ongoing for several decades. It has been used to one degree or another in industries such as aerospace, electronics, chemical processing, nuclear reactor containment, construction and transportation. It has evolved from a method for the design and diagnosis of safe systems to one that also has applicability in Reliability Engineering. The more general term, Event Tree Analysis, refers to a method for examining the events that lead to either mission success or mission failure. The more restrictive term, Fault Tree Analysis, refers to a failure oriented analysis. Hence the top event in a fault tree has generally an event description that depicts mission or system failure. Most of the events in a fault tree that support and contribute to the top events are undesirable ones and are appropriately named faults.

With minor modifications to the conventional symbology used in current FTA, the objective of this work is to provide a model of an Anti-Aircraft Warfare (AAW) scenario from a mission failure (or defensive) point of view.

It should be emphasized that the methodology used in this paper has the potential for use in other scenarios either

operational or non-operational. In the broader sense of Event Trees, the potential to analyze not only mission failure but the more positive side, mission success appears to be unlimited. The results can be used as both a quantitative predictive and a qualitative instructional tool.

The inherent objective in Fault Tree Analysis is to provide an in depth analysis that is understandable by others. This requires that the modelor (or analyst) completely specify the combinations of events occurring in the system, and how they lead to the top event through a logical use of symbols and graphs.

In FTA one of the quantitative goals is to compute an overall probability of mission success or failure. Simply stated, FTA will predict the occurrence of the top event with a certain probability. The AAW model examined in this work is not used as a quantitative predictor but instead examines in a qualitative manner the events that lead to mission failure.

As a qualitative tool FTA provides a method when properly used, that could lead to the discovery of events or combinations of events that may not have otherwise been recognized as causes of the event being analyzed. For further discussion and treatment of the use of Fault Tree Analysis it is suggested that the reader consult the articles contained in Barlow, Fussell and Singpurwalla, [Ref. 1], and cited in Barlow, [Ref. 2].

B. THE ANTI-AIRCRAFT WARFARE MODEL

The tactical importance of anti-aircraft warfare makes it a logical choice as a topic for Fault Tree Analysis. In addition, an abundance of information consistent with current tactical thinking on the AAW problem is readily available and adaptable to FTA. Simply stated, the AAW problem concerns the destruction of enemy air platforms and airborne weapons whether launched from surface, sub-surface or air platforms. The model considered in this work is for the AAW problem restricted to air platforms that launch missiles against U.S. naval aircraft carriers and their escorts. The problem scope now becomes the defense of an aircraft carrier against long range bombers (LRB's) that launch long range air-to-surface missiles (ASM's). In order to reduce the problem to one that is manageable, the normally assumed 360 degree circle of protection that is required about the carrier now becomes a smaller sector of undefined size where one-on-one engagement analysis is performed. This is not an unreasonable assumption with the state of alertment associated with today's early warning detection systems and military intelligence systems. Applying fault tree methodology from the defensive point of view, the top event corresponds to the aircraft carrier being hit by one air-to-surface missile (ASM) launched from a long range bomber (LRB) at some standoff launch range. The aircraft carrier is protected in the sector by airborne early warning aircraft, long range combat air patrol aircraft

(CAP) and medium range CAP, a long range surface-to-air missile (SAM) ship, a short range SAM ship and the carrier's own self defense system (commonly called point defense system). By convention the model is developed "top down" through the contributory events that build to a hit on the carrier. During application however, the flow of occurrences through the logic gates is directed upward.

C. SUMMARY

In summary, this paper examines a modified version of Fault Tree Analysis applied to an Anti-Aircraft Warfare scenario. The features of event tree analysis are examined with a look toward both quantitative and qualitative application. Finally an examination of how this methodology may be used in other operational or non-operational scenarios is conducted.

II. EVENT TREE CONSTRUCTION

A. EVENT SYMBOLOGY

The top event in a fault tree is generally some undesired system state resulting from a combination of undesired subsystem states. Since the tree is developed top down, the top event must be carefully and thoughtfully defined and then the tree developed by modelors or analysts who have a fairly detailed understanding of the system and who can translate that knowledge into a graphical representation.

The methodology for Fault Tree Analysis that has been adopted in this paper is a simplification of the standard methodology found in current works on Fault Tree Analysis. Specifically, the symbology used in Barlow and Lambert, [Ref. 3], and Young [Ref. 4], has been modified for the convenience of using computer generated graphics to display the AAW model. The EVENT symbology used in this work does not alter the logic or the event sequence associated with the symbology cited in the references. Although it replaces the use of the four event symbols in Figure 2.1 by a single symbol, the rectangle, used to display all events in the model, no information is lost in this representation. Within the rectangle an undesired system state is defined. Whether or not it is classified as a primary event, a secondary event, an undeveloped event or a switch event is not important in the application presented here.

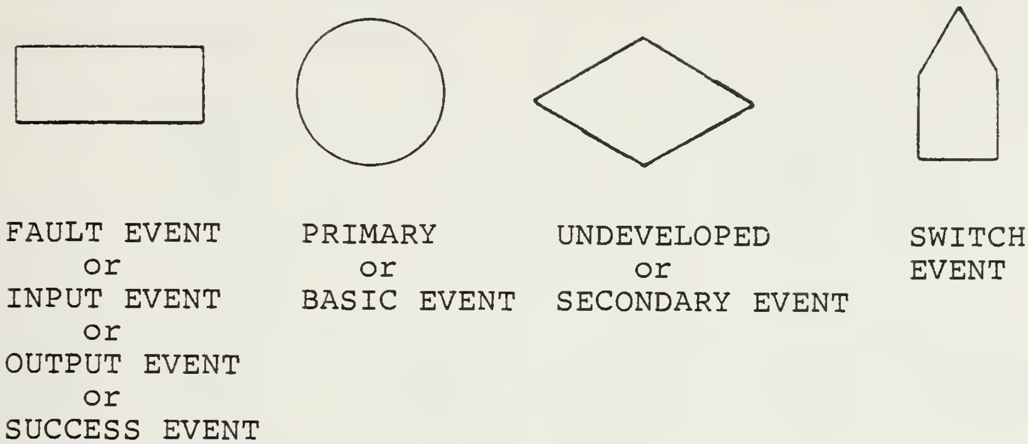

Figure 2.1 FTA SYMBOLOGY

B. LOGIC SYMBOLOGY

The two most often used symbols to connect the contributory events to the top event are the two logic gates, the AND gate and the OR gate. In a mathematical sense the AND gate represents set intersection while the OR gate represents set union. In Figure 2.2 undesired Event One will result only if Event Two and Event Three and Event Four occur. Event One is the result of transmitting Events Two, Three and Four through the AND gate. To illustrate the use of the OR gate, undesired Event Five will result if at least one of the events, Six, Seven or Eight occur.[1] By transmitting Events Six, Seven and Eight through the OR gate, Event Five will result. The tree is structured so that all events lead sequentially and

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[1]The symbology used here follows closely the symbology used in current work with the exception that some modelors use a combinatorial OR gate such as 1 out of 3, or 2 out of 4, etc.

logically to the top event, and all are related to the top event by AND and OR gates.

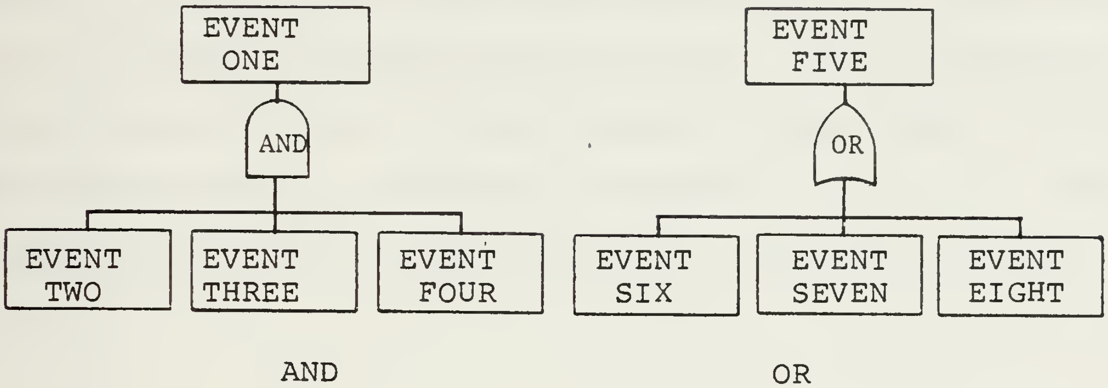


Figure 2.2 LOGIC SYMBOLOGY

C. SUCCESS TREE VERSUS FAULT TREE

The term "success tree" to which prior reference has not been made is another application of event tree analysis that can result in a better understanding of the system being analyzed. To contrast the use of success trees and fault trees, consider the Initial Scenario proposed in the illustration below. The illustration forms the basis for the AAW model examined later.

The Initial Scenario can be stated as follows: The carrier is attacked by a single aircraft. The aircraft attempts to close to a range which permits the launch of its one air-to-surface missile. The Initial Scenario is displayed in Figure 2.3.

From a defensive point of view the modelor could apply either of the two methods, Fault Tree Analysis or Success

Tree Analysis to logically symbolize the events that lead to the top event. His choice may be purely one of preference or there may be underlying assumptions that would cause him to choose one method over the other. To illustrate the dual relationship that exists between the two trees, consider the events that are displayed in Figures 2.4 and 2.5. These figures develop the tactical scenario displayed in Figure 2.3.

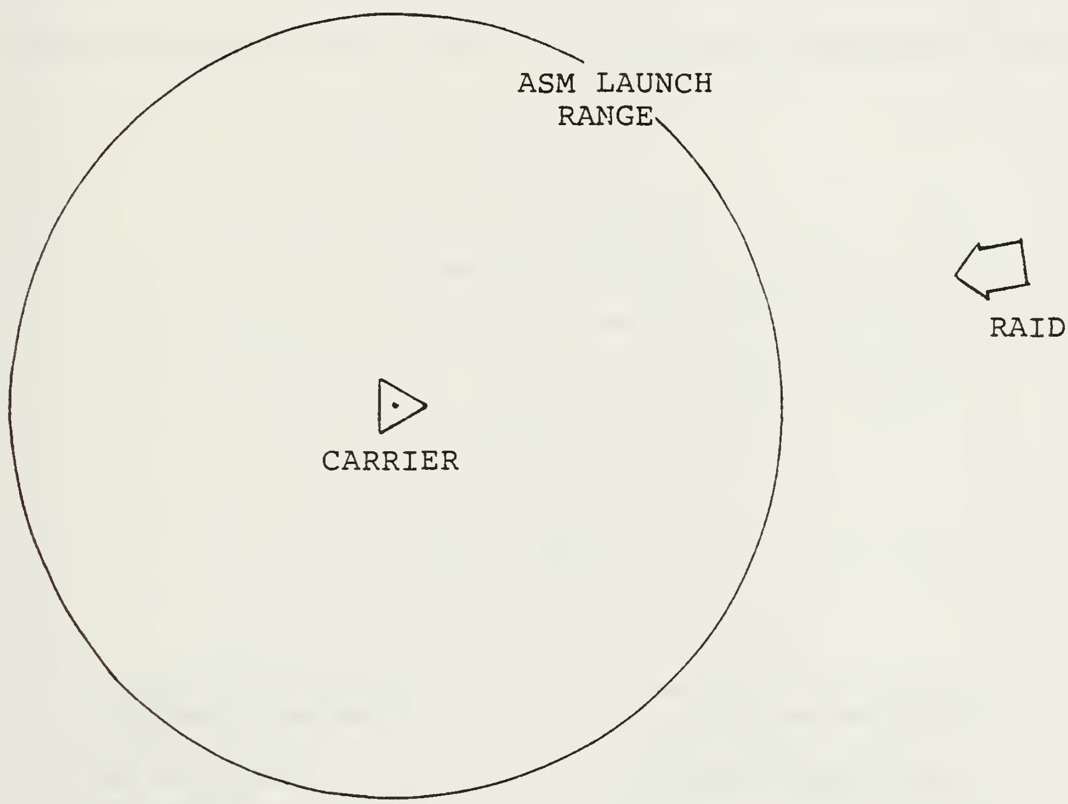


Figure 2.3 INITIAL SCENARIO

Figure 2.4 shows a success tree, with application of the OR gate. It relates a top event which is favorable to the defense to the contributing favorable events.

Figure 2.5 shows a fault tree, with application of the AND gate. It relates a top event which is unfavorable to the defense to contributing unfavorable events.

In addition to providing graphic representation of success tree versus fault tree methodology, the "dual analysis" displayed in Figures 2.4 and 2.5 illustrate the simple manner in which the OR gate and the AND gate can be used interchangeably by negating the top event (or any fault/success event).

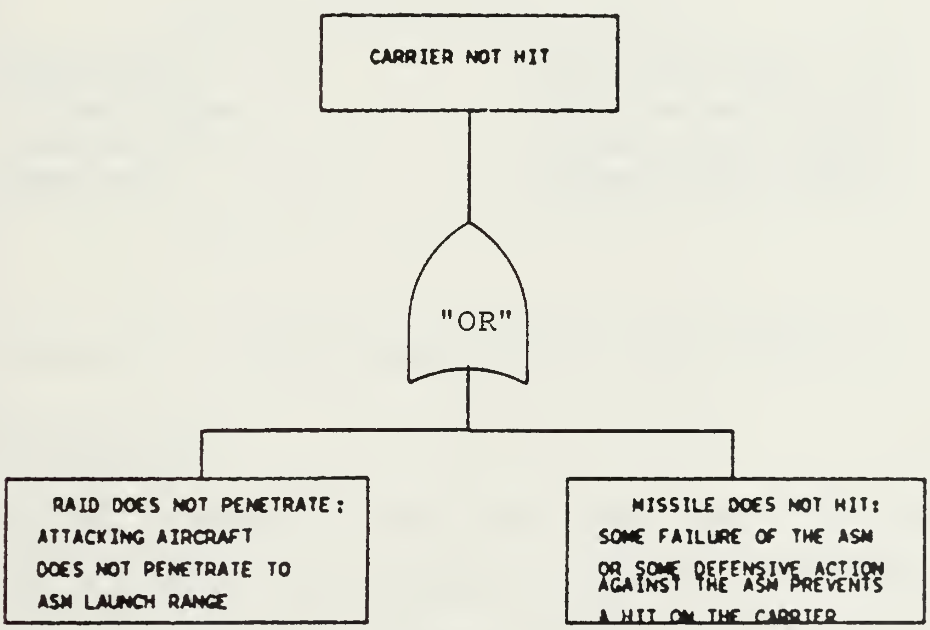


Figure 2.4 SUCCESS TREE WITH OR GATE APPLIED

The Initial Scenario and the contributing examples are extracted from unpublished notes by J.D. Esary, Professor of Operations Research and Statistics, Naval Postgraduate School. The probability analysis of Appendix A is extracted from the same notes.

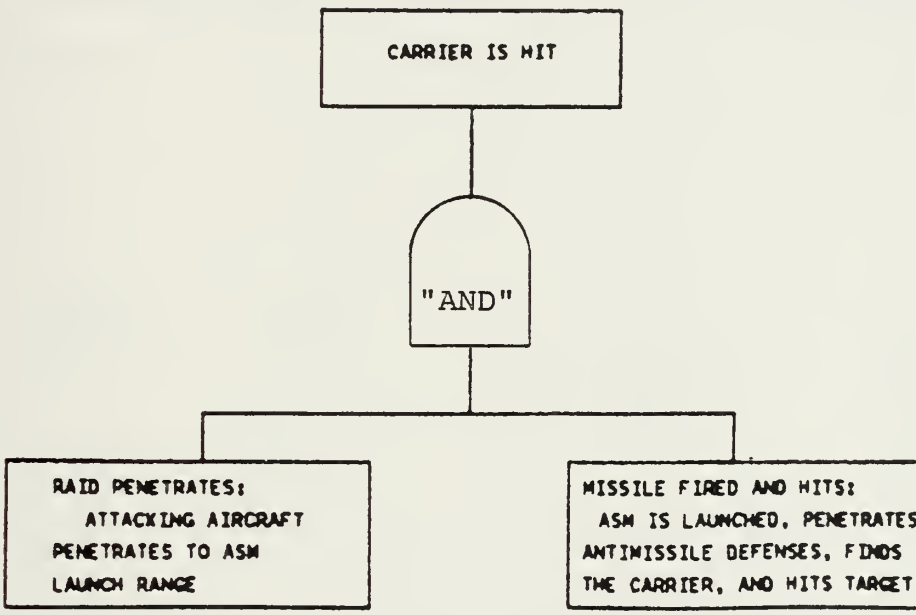


Figure 2.5 FAULT TREE WITH AND GATE APPLIED

D. IMPLEMENTATION

The model examined in this work uses Fault Tree methodology while using the symbology similar to that indicated in Figures 2.4 and 2.5. The most notable difference is that both the AND and OR gates are represented by one shape and that shape is rotated 180 degrees from those of Figures 2.4

and 2.5. This shape will become familiar in the next chapter. Since the model is too large to fit on one sheet of standard size paper, "off page" connectors are used to continue the model on subsequent pages. The off page connector, a small circle with the connector page number located inside, is easily located on each page of the model. Logic gates and off page connectors used throughout this work are displayed in Figure 2.6.

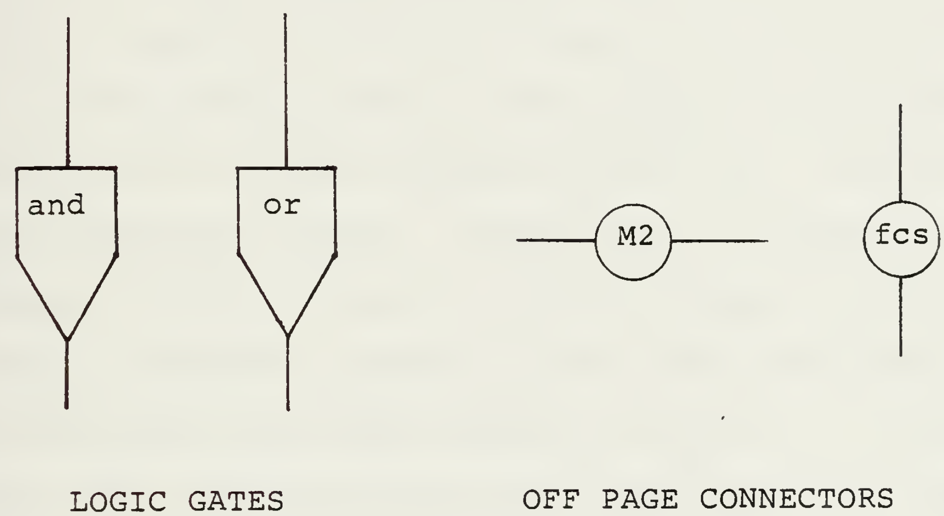


Figure 2.6 LOGIC GATES AND OFF PAGE CONNECTORS

III. FAULT TREE MODEL

A. DEFENSE IN DEPTH

Although the objective of this work is not to examine the tactics used by a modern naval combatant task force against a long range bomber/antiship missile threat, an understanding of the defensive concepts used in such a scenario will assist in the understanding of the model.

The air defense of the U.S. naval battle group is centered on the aircraft carrier and is based on the aggregate support from all of the elements in the group. This concept is called defense in depth. Three zones of defense are used to describe defense in depth. Various weapons systems are employed at different ranges to prevent the penetration of enemy platforms (Long Range Bombers or ASCM's). The defensive barriers that are implied here are created by long range and medium range CAP aircraft in the Outer Defense Zone; by long range and short range SAM ships in the Inner (or Area) Defense Zone; and by the individual ships point defense systems in the Self Defense Zone. The geographical boundaries to each zone have been generally defined and are based on the maximum ranges of the various weapons systems. With modern weapons systems the ranges become somewhat flexible and in many cases overlap. This is especially evident when one considers the maximum range of the air intercept missiles (AIM's) used by fighter aircraft versus the range of the LR SAM.

The problem with overlapping weapons coverage is truly a dynamic one that results in subsequent weapons allocation problems. When one considers the speed of the incoming ASCM, this problem becomes even more evident. Once the ASCM is detected, very little time remains to decide on the best method to counter the penetrator. This problem exists not only in the inter zone sense (CAP vs LR SAM for example) but also in the intra zone sense (which CAP or LR SAM platform to assign). For the AAW scenario the task of assigning weapons to ASCM (or LRB) is the responsibility of the ANTI-AIR WARFARE COMMANDER. The problem becomes more severe when electronic warfare measures are employed by both the offensive and defensive platforms to degrade the opponent's use of electromagnetic radiation.

Outer Air Defense Zone tactics are designed to allow outer air defense forces to detect and destroy antiship cruise missile (ASCM) platforms (LRB's) before the launch of the ASCM. Accompanying the long range bombers are electronic jamming aircraft, commonly called STRIKE SUPPORT aircraft, that provide electronic support and protection of the LRB's at STANDOFF ranges. Outer defense zone tactics further include the destruction of these platforms. The scenario modeled in this work does not explicitly include the attempt to knock down these platforms, however the jamming provided by the strike support aircraft is modeled.

Since the primary objective of the LRB is to target the carrier and subsequently launch an ASCM, the advantageous position from which to do this is at the maximum range from the task force. The LRB thereby reduces time in which he is exposed to the task force CAP aircraft. This range generally corresponds to the maximum range of the ASM and is termed the STANDOFF launch range.

The LRB uses active radar to accomplish this task, an active radar that may be vulnerable to electronic countermeasures by members of the battle group. The term that is applied to the use of electronic countermeasures by the battle force is COUNTERTARGETING. As the term implies, COUNTERTARGETING is the use of active or passive jamming to reduce the range at which the long range bomber can accurately detect and target the aircraft carrier.

What we have seen in the Outer Air Battle is a reduction in the number of standoff jammers with the use of CAP aircraft. The attrition of standoff jammers is essential to the defense of the carrier if the battle group radars are expected to detect ASM platforms before cruise missile launch. Outer air battle forces thus reduce the number of attackers that penetrate to the Inner Defense Zone. Finally, the outer air forces are used to destroy loitering or retiring long range bombers so that follow-on raids are less severe.

Before proceeding, it may be advisable to consider the tradeoffs that exist in the Outer Air Battle when offensive

and defensive electronic countermeasures are employed. The offensive LRB prefers to target the carrier at maximum standoff range in order to launch the ASM (which needs no further guidance from the bomber once launched). The LRB thus reduces his exposure to the layered defensive forces. The tradeoff here stems from the fact that at maximum standoff range the targeting problem is more severe than at reduced ranges where targeting solutions are more accurate. Thus the effectiveness of his attack is reduced. Conversely the defensive forces, or battle group, use electronic means to increase the targeting problem and thereby force the bombers to proceed to ranges more precarious to their survival. More importantly, the probability that an ASCM is launched is reduced.

In the Area Defense Zone long range and short range surface-to-air missiles are employed to destroy penetrating ASCM's. Electronic countermeasures are used to deceive the ASCM's. Depending on the effectiveness of the countertargeting, an additional problem of command and control exists with overlapping engagement zones. CAP-SAM coordination is necessary to prevent engagement of defender-on-defender. The coordination of inner defense weapons is necessary to prevent overengagement of one target while others remain unengaged. Thus real-time management of weapon resources is mandatory in the hostile environment created by the launch of an ASCM.

The Self Defense Zone constitutes the final barrier in the defense of the carrier. This zone employs point defense

systems (missiles or guns) that have high kill probabilities to destroy the ASCM's that have penetrated the outer zones.

B. ASSUMPTIONS

The AAW model examined in this work uses the defense in depth concept to describe the events that lead to a hit on the carrier. Prior to the assembly and description of the fault tree, it may prove useful to describe the tactical and strategic assumptions that were used to design the model.

The assumptions are:

- Carrier battle group is attacked by long range bombers in open ocean transit.
- Antiship cruise missile is autonomous after launch; no midcourse update or corrections are necessary from the mother aircraft.
- Antiship cruise missile flight profile is high altitude in the cruise phase and steep angle of attack in the dive phase.
- All defensive forces are modern platforms that are equipped with the latest variant of Navy Tactical Data System (NTDS).
- Outer air battle forces are comprised of Early Warning (AEW) and fighter aircraft using vector logic techniques for detection, tracking and engagement of hostile platforms.

- Although there may be many LRB's in the raid that attack the carrier, this analysis deals with only one small sector close to the threat axis.
- Each LRB has only one ASCM.
- Salvo doctrine for the defensive forces is implicit and imbedded in the fault tree; i.e., how many missiles it takes to hit the ASCM is not important, just that the event did or did not happen.
- Approximate threat axis is known.
- Area defensive forces are NTDS equipped.
- Long range missile ship employs Terrier missile system to intercept the ASCM.
- Short range missile ship employs Tartar missile system to intercept the ASCM.
- LR SAM ship is positioned for cruise phase intercept of the ASCM.
- SR SAM ship is positioned for dive phase intercept of the ASCM.
- LR and SR SAM ships have electronic warfare suites permitting countertargeting techniques.
- Composite Warfare Commander (CWC) doctrine is used.
- Countertargeting, when effective, is only effective in the Outer Defense Zone.

- Some probability exists for a LR/MR CAP to intercept the high altitude ASCM with CAP-fired air intercept missiles (AIM's).

C. THE MODEL (EXPANDED VERSION)

Since the model was developed top down to conform to the convention in Fault Tree Analysis, the top event is assigned "Carrier is hit". As previously discussed it is the major event to which all subevents subscribe. To get an overview of the events that must be further developed the following analysis is provided.

The event "CARRIER IS HIT" is a result of:

- Missile penetrates point defense systems.
- Missile penetrates short range SAM ship defense.
- Missile penetrates long range SAM ship defense.
- Missile penetrates LR/MR CAP defenses.
- Missile launched from long range bomber.
- Countertargeting is effective, LR bomber penetrates LR/MR CAP defenses to reduced launch range.

  OR

  Countertargeting is ineffective; LRB penetrates LR/MR CAP defenses to standoff launch range.

The events listed above are the major subsections of the model. Figure 3.1 displays these major events by block diagram. Developing the sub events that appear in Figure 3.1 and applying fault logic to the model is the next step in the procedure.

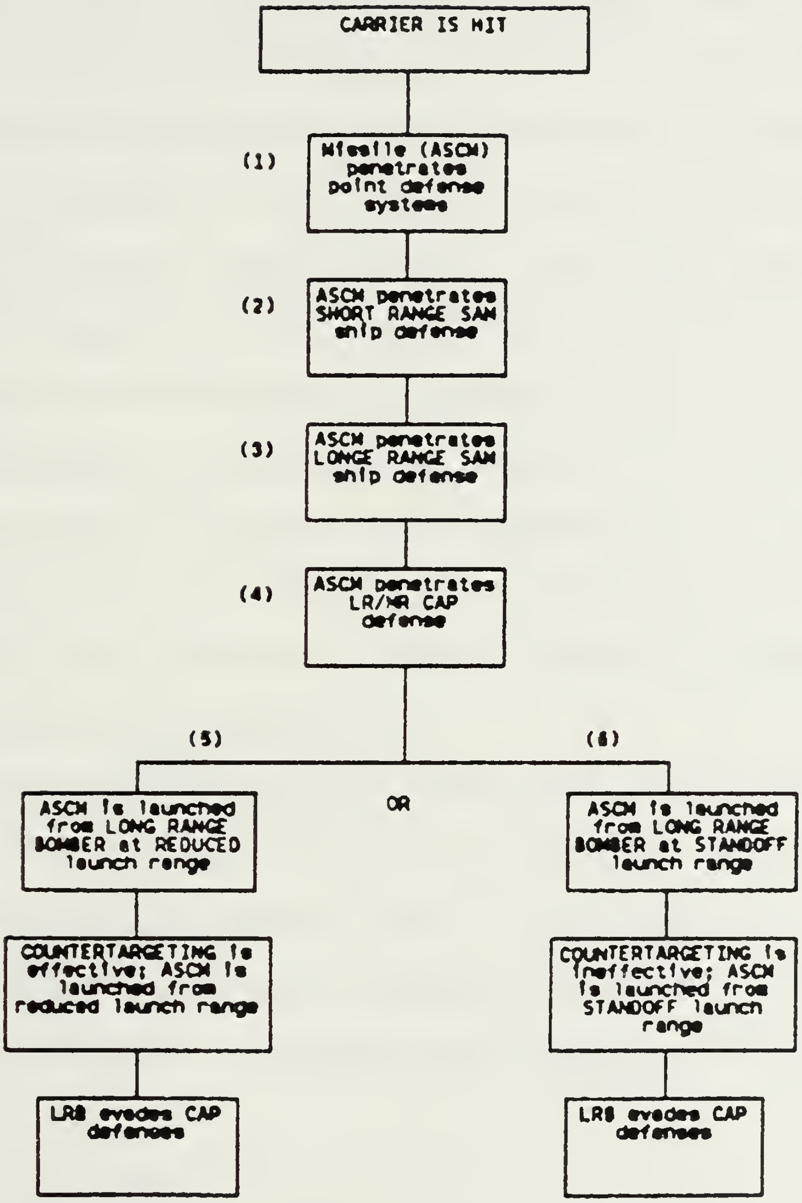


Figure 3.1 BLOCK DIAGRAM

D. HOW TO READ THE MAJOR SUBEVENTS

The block diagram presented in Figure 3.1 was used as a starting point to gain an overall appreciation for the model. An expanded version of the model with fault tree symbology applied is presented in Figure 3.2 and continued in Figure 3.3. The model was developed from the block diagram using a "tiered" approach. Each tier represents a combination of subevents that are linked together with logic gates. Each tier is in actuality composed of many subevents but only the major events are displayed in Figures 3.2 and 3.3. The numbers that appear in parentheses adjacent to each block (or group of blocks) in Figure 3.1 correspond to the tiers in Figures 3.2 and 3.3. The tiers are correspondingly numbered also. The tiers represent specific levels of defense through which the ASCM must penetrate.

Applying this nomenclature and using the Defense in Depth concept, block (1) in Figure 3.1 relates to the Self Defense Zone. This corresponds to tier (1) in Figure 3.1. Similarly, blocks (tiers) (2) and (3) represent the Area Defense Zone and blocks (tiers) (4) through (6) relate to the Outer Defense Zone.

1. First Tier

The Self Defense Zone of the carrier is developed from the primary fault event of the tree or the top event. The event "Carrier is hit" results from two events that comprise the first tier of the model. The ASCM must first

penetrate the POINT DEFENSE system of the carrier and the ASCM must function properly in the terminal (homing) descent phase.

It should be noted that the model presented here is a one sided model, because the events displayed represent only the faults of the defensive force (the battle group). With few exceptions, the faults (or successes) of the offensive force are not presented. One instance that is contrary to this convention occurs in the first tier. The event "ASCM systems function properly" is a major offensive force event.

2. Second Tier

ASCM penetration of the carrier SELF DEFENSE ZONE is a result of two major subevents: (a) the missile has penetrated the SR SAM ship DEFENSE ZONE and (b) the missile has evaded the carrier's Point Defense Zone. Event (b) does not appear in Figure 3.2. It is the implicit combination of two events that are connected through a logic gate. The evasion of the carrier's point defense system is a result of the union of two events: either (b1) carrier fires it's point defense system at the ASCM and misses or (b2) the carrier does not fire.

3. Third Tier

Tier (3) represents the final tier in the Inner Defense Zone. The penetration of the ASCM through the SR SAM ship defense is a result of transmitting the event "ASCM penetrates through LR SAM ship defense" and ASCM evasion of the SR SAM

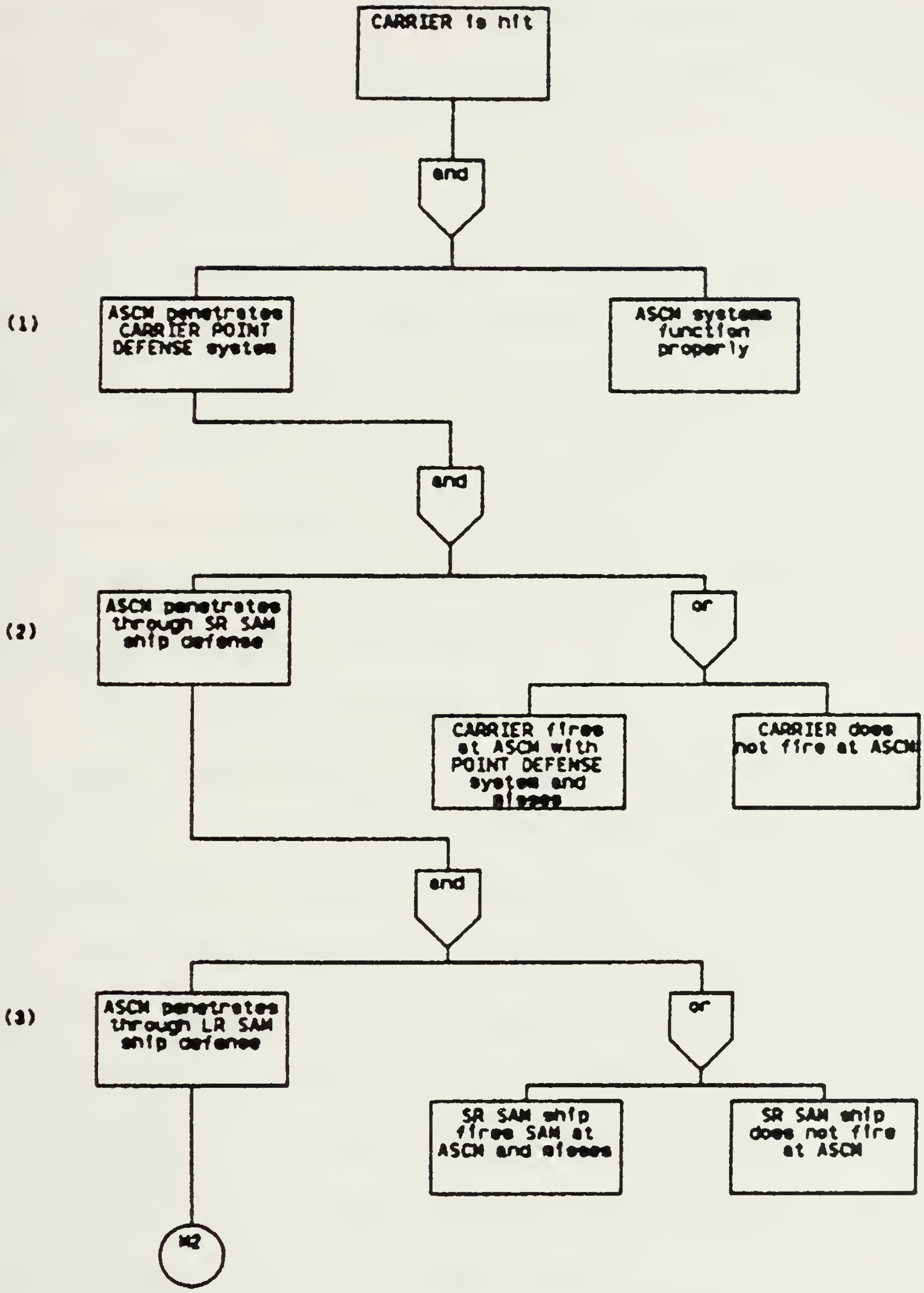


Figure 3.2 MAJOR SUBEVENTS

ship defense through an AND gate. ASCM evasion of the SR SAM ship defense is not an explicit event in Figure 3.2 but a combination of two events that are connected by an OR gate: either (a) the SR SAM ship fires and misses or (b) the SR SAM ship does not fire.

4. Fourth Tier

The penetration of the ASCM through the LR SAM ship defense is a result of ASCM penetration through the CAP defenses and the intersection of ASCM evasion of LR SAM ship defense indicated in Figure 3.3. The latter event is a combination of two events: (a) LR SAM ship fires a LR SAM and misses or (b) LR SAM ship does not fire. These events are transmitted through an OR gate.

5. Fifth and Sixth Tiers

ASCM penetration to the Inner Defense Zone is a result of many fault events in the Outer Air War. To put it into perspective, return to Figure 3.1. The ASCM is launched from a long range bomber at a position within the maximum range of the ASCM after the mother aircraft has gained accurate targeting information on the carrier. Depending on the effectiveness of the countertargeting efforts of the battle force, the ASCM will be launched either from a STANDOFF launch range or from a REDUCED launch range.

Return now to Figure 3.3. At tier (4), ASCM penetration through the CAP defenses is a result of connecting the essential event of tier (5) "ASCM is launched from REDUCED

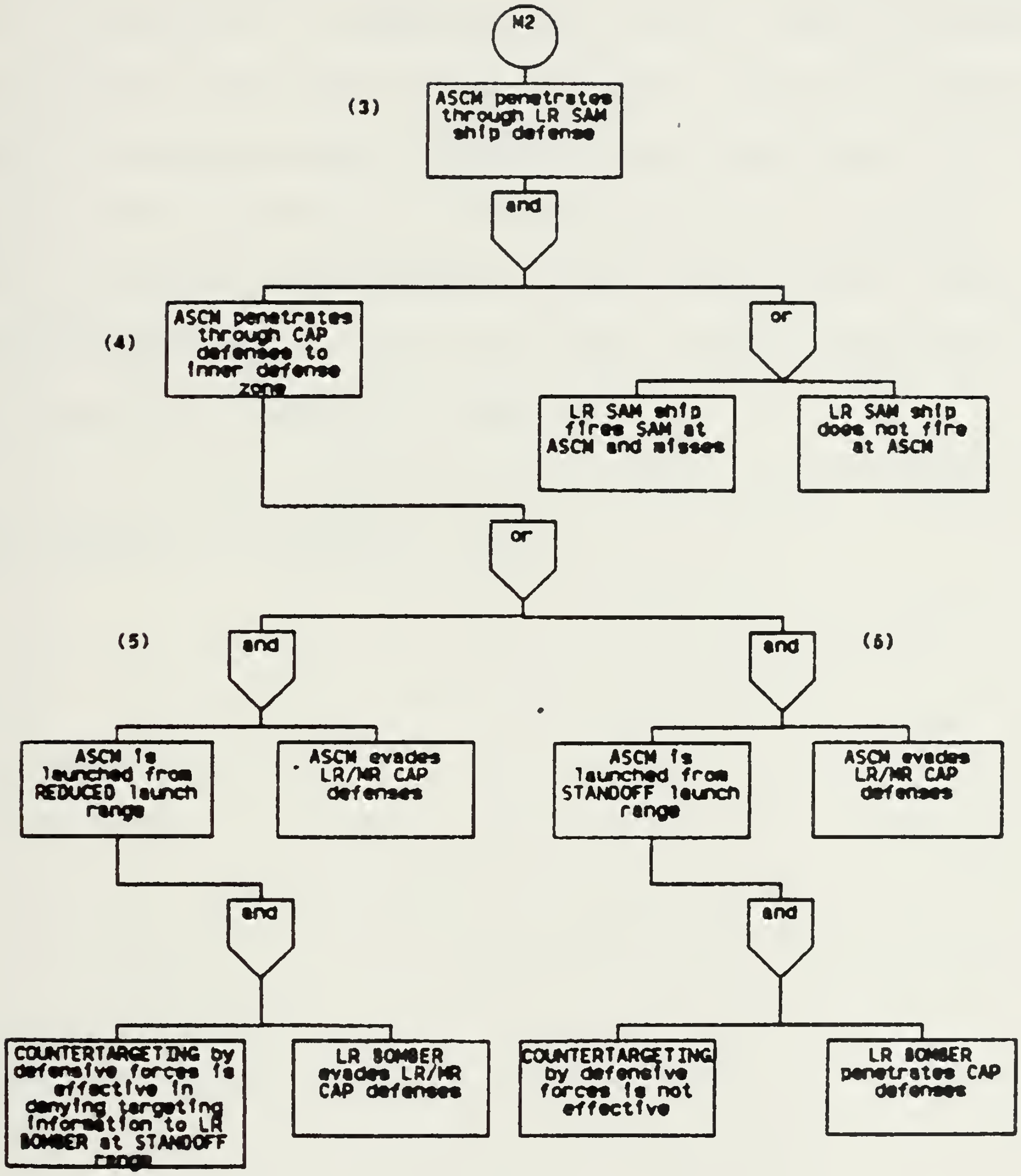


Figure 3.3 MAJOR SUBEVENTS

launch range" with the essential event of tier (6) "ASCM is launched from STANDOFF launch range". These tiers are connected by an OR gate. Tiers (5) and (6) are further developed in Figure 3.3. Referring to tier (5), once launched, the ASCM must evade the CAP-fired AIM's. The two events (a) "ASCM is launched from a REDUCED launch range" and (b) "ASCM evades LR/MR CAP defense" are connected by an AND gate. The ASCM is launched from REDUCED launch range because the events "COUNTERTARGETING ..." and "LR bomber evades LR/MR CAP defenses" are transmitted through an AND gate.

A parallel analysis can be seen in tier (6) for the ASCM launched at STANDOFF range.

IV. THE DETAILED MODEL

Chapter III presented the AAW model in an expanded version. A tiered approach was developed to gain an appreciation for the construction of the model. The intention in the present chapter is to detail the model.

A. SELF DEFENSE (TIER 1)

The fault events that contribute to the penetration of the ASCM through the self defense system of the carrier are displayed in Figure 4.1. The primary difference between the events of Figure 4.1 and those of Figure 3.2 is the expansion of the major subevent in Figure 3.2: "Carrier fires ... and misses". Three events connected by an AND gate describe this event. Consider the first event (reading left to right). In order to fire the ASCM there must be a fire control solution generated on the carrier. Once the solution is found by the fire control system (block 2), the carrier fires at the ASCM and misses.

The events that lead to a fire control solution are presented in Figure 4.2. The events are connected to Figure 4.2 by the "fcs" off page connector. Events similar to those of Figure 4.2 are used throughout this work since a fire control solution must be performed prior to firing any weapon. Conceptually there is little difference in generating a fire

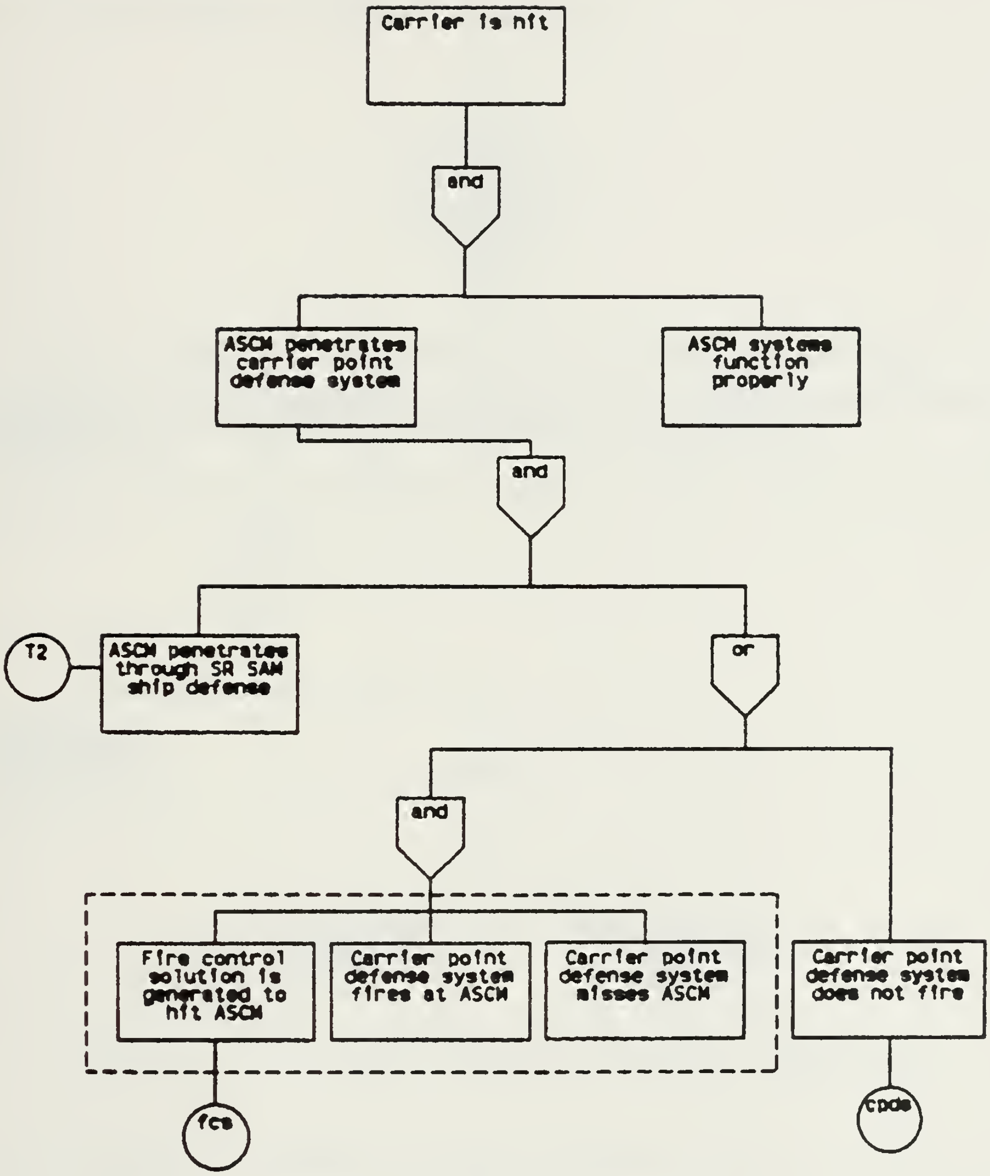


Figure 4.1 ASCM PENETRATES SELF DEFENSE SYSTEM

control solution whether on the carrier or on another NTDS equipped vessel. Furthermore, although the details of this analysis imply NTDS, the development is general enough to use for non-NTDS equipped platforms.

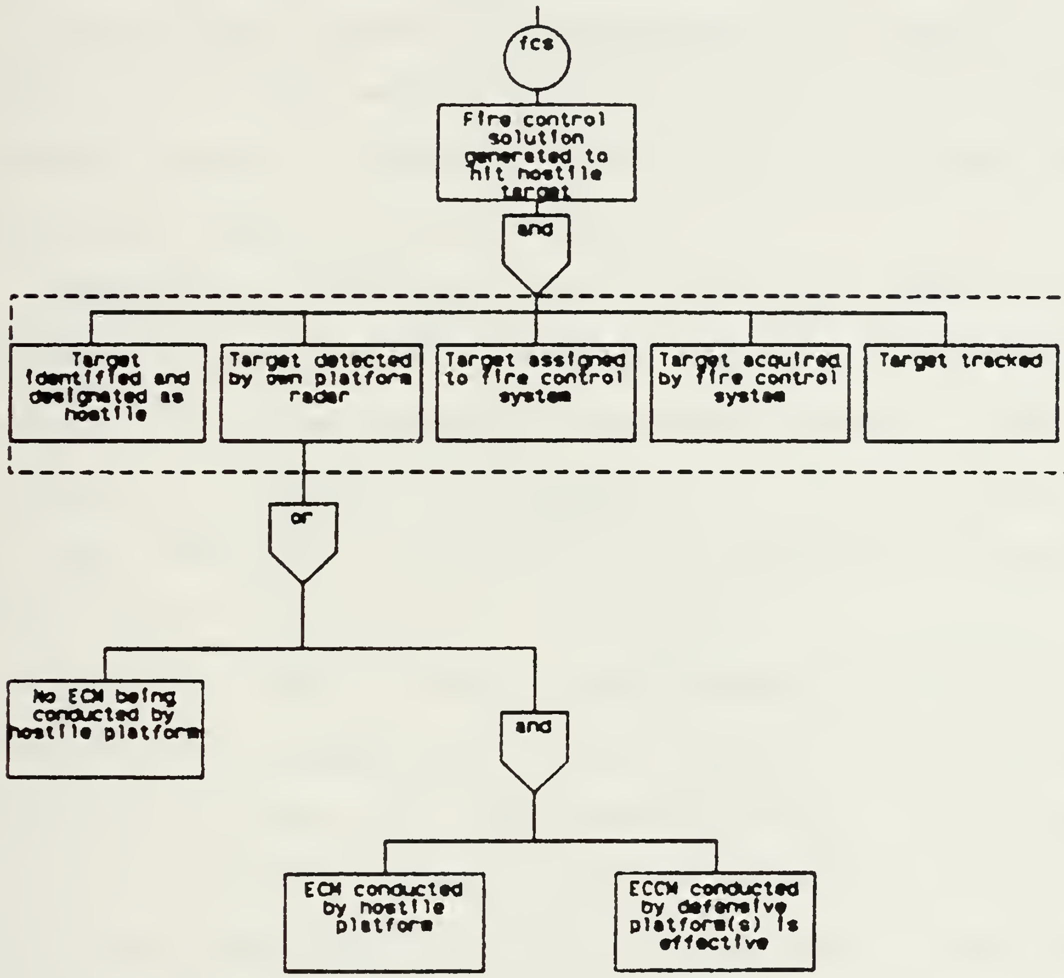


Figure 4.2 FIRE CONTROL SOLUTION GENERATED

The blocks enclosed by the dashed line in Figure 4.2 are read as follows: a target has been designated "hostile" by some other unit (AEW, LR SAM SHIP, CAP); the target is detected by the carrier's radar and and the symbol that appears on the NTDS console (visual display) matches the hostile

designation. A fire control system (there may be more than one) on the carrier is designated to perform the task of firing the weapon at the ASCM. The fire control system "acquires" the target and then "tracks" the target. Finally, a "solution" to the intercept problem (Point Defense versus ASCM) is computed. All of the events that are enclosed by the dashed line must happen in order to close the loop, therefore the events are connected by an AND gate.

Detection of the target with a ship's own radar is constrained by the electronic measures taken by the STRIKE SUPPORT aircraft. In order to detect the target, either "No ECM is conducted ..." or "ECM is conducted ...". If the latter is the case then ECM is countered by the self defense system. These events are displayed in Figure 4.2.

The event "carrier point defense system does not fire" in Figure 4.1 is supported (via the "cpds" connector) by events displayed in Figure 4.3. The system does not fire for one of several reasons: either (1) the "Fire control (FC) solution is not generated" or (2) the "FC solution is generated but a command and control problem prevents firing" or (3) the "fire control solution is generated and the launcher malfunctions".

The FC solution events in Figure 4.3 are supported by the events displayed in Figure 4.4. The hostile target is not engageable because (a) either the target is out of the engagement envelope of the fire control system (unlikely in

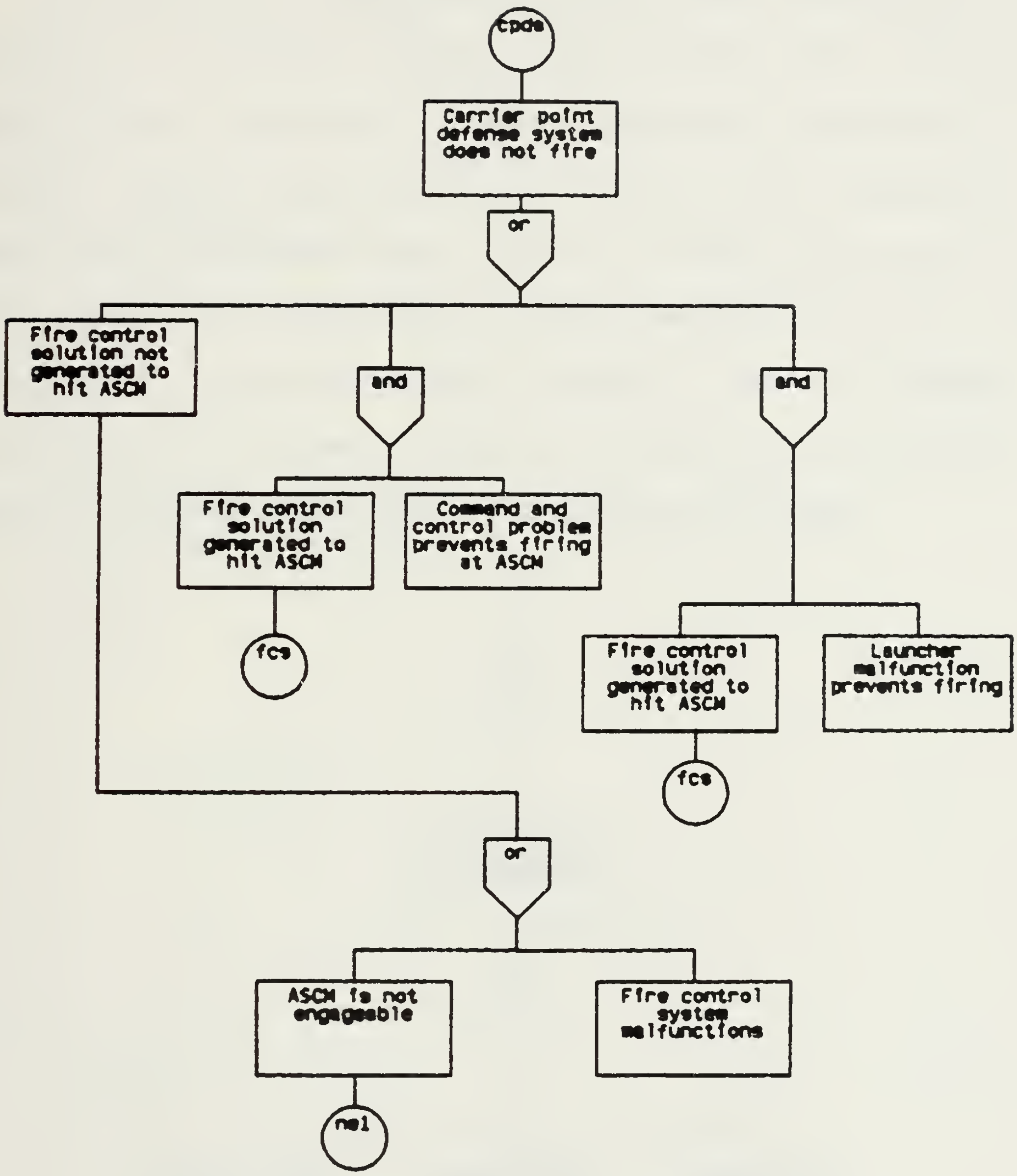


Figure 4.3 CARRIER POINT DEFENSE SYSTEM DOES NOT FIRE

this case since the ASCM's goal is to hit the carrier) or (b) the detection of the ASCM is gained late or (c) the detection of the ASCM is not made.

To amplify the meaning of the off page connectors, the following conventions apply. The acronym "fcs" represents "fire control solution", "cpds" represents "carrier point defense system" and "nel" translates to "not engageable". Lower case connectors move "down" the page and connect to minor subevents while upper case connectors generally move "across" the page and connect to major events or tiers. This convention is relaxed in Figure 4.7 where the connectors T5 and T6 tie downward rather than across the page.

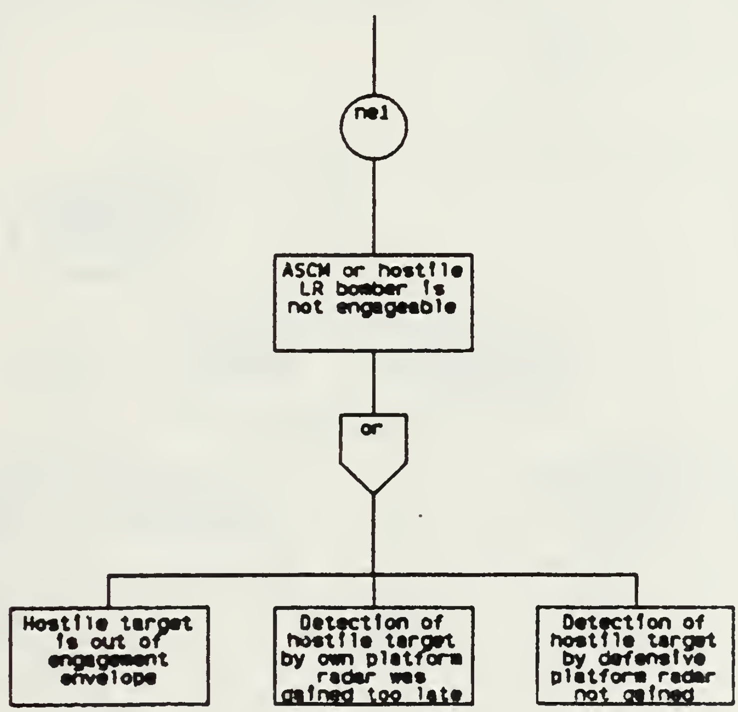


Figure 4.4 ASCM OR LR BOMBER NOT ENGAGEABLE

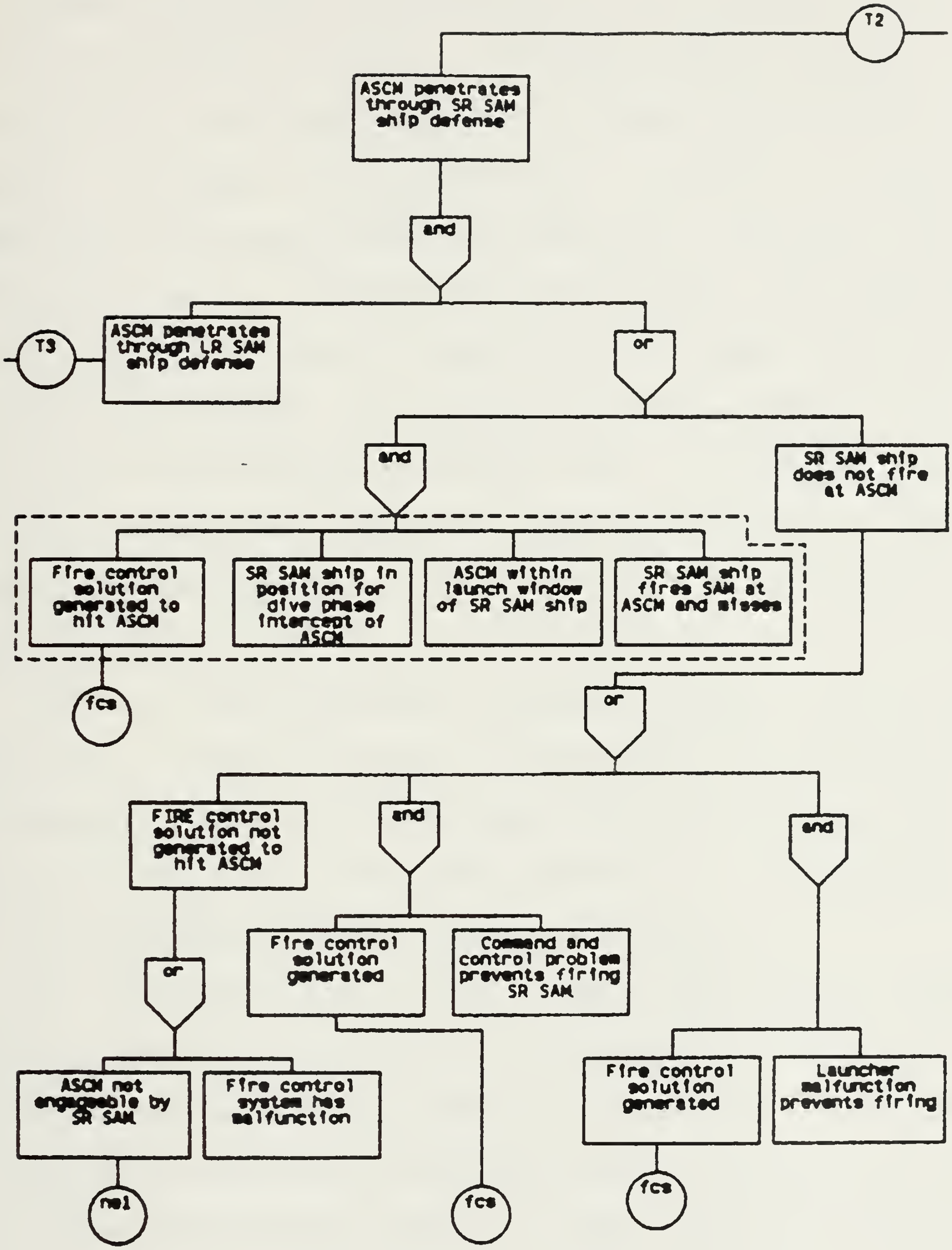


Figure 4.5 ASCM PENETRATES SR SAM SHIP DEFENSE

B. SR SAM SHIP DEFENSE (TIER 2)

SR SAM ship defense system events are connected to Figure 4.1 by the "T2" connector. They are shown in Figure 4.5. Penetration of the ASCM through the SR SAM ship defense is similar in concept to the first tier. In general, a target (ASCM) must be present that has penetrated a previous tier and a fire control solution must be generated. The defensive platform can either fire or not fire at the ASCM, depending on the circumstances. One notable difference concerns the four events enclosed by the dashed line. It relates to the position of the ship. Since the ASCM is targeted for the carrier, ship positioning in the case of a SR SAM ship becomes an issue.

The four blocks represent the major subevent "SR SAM ship fires SAM at ASCM and misses". The events are connected by an AND gate. Thus all events must occur in order to have a firing. The first event, "FC solution ..." is supported by the contributory events listed in Figure 4.2.

The second and third events (reading from left to right) appear to be similar structurally and semantically but are separated to emphasize the issue. Although one of the events places the SR SAM ship in the approximate location, in range and on the AAW axis for firing the SAM, the event is included as a necessary ingredient to the problem solution. If not positioned optimally, the probability of hitting the ASCM becomes less than desired. In addition to positioning, timing

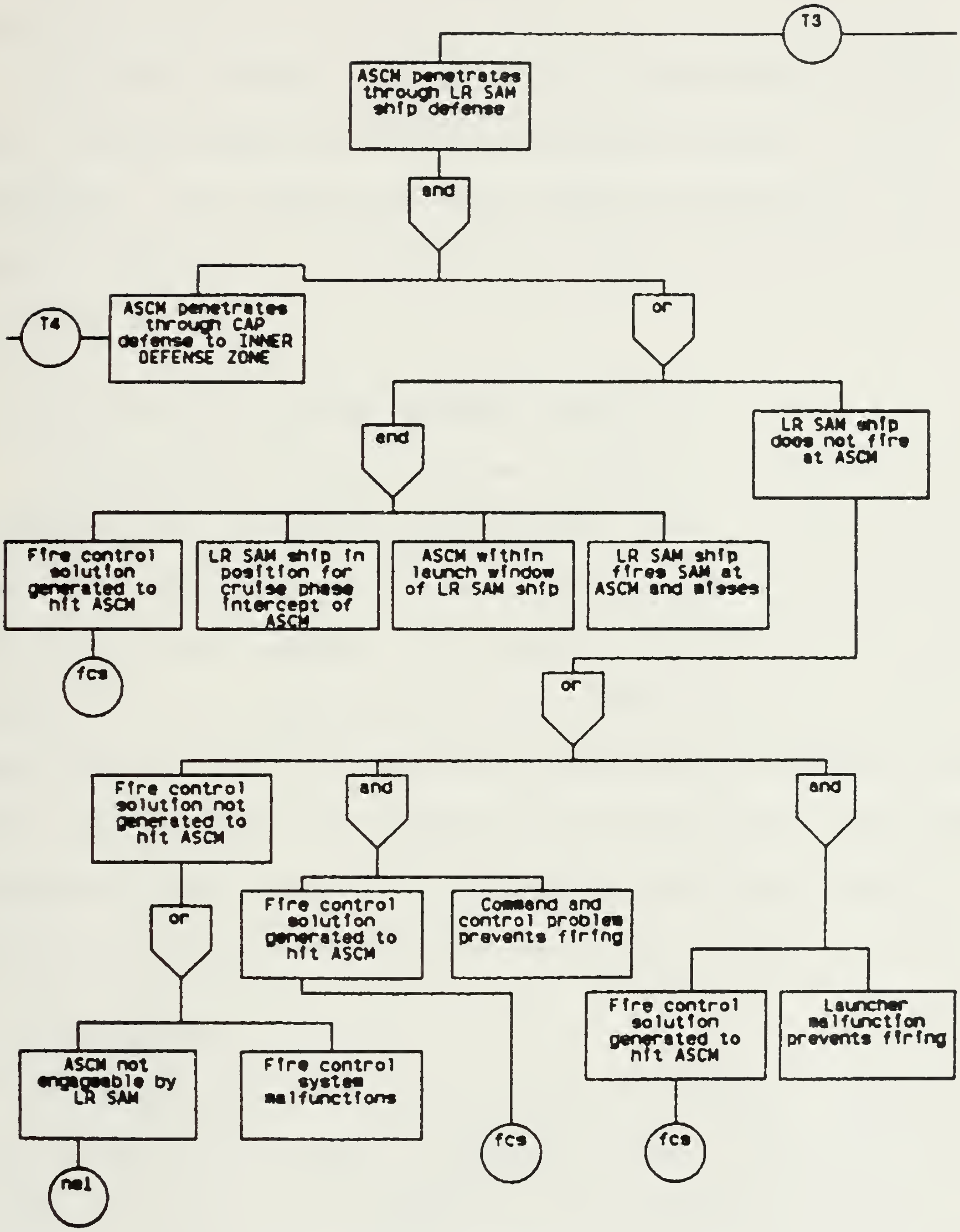


Figure 4.6 ASCM PENETRATES LR SAM SHIP DEFENSE

the SAM launch is important. Consequently the event "ASCM within launch window of SR SAM ship" is included in this analysis.

The fourth event enclosed in the dashed box in Figure 4.5, "SR SAM ship fires SAM at ASCM and misses" is self explanatory. The remaining fault events displayed in this portion of the model are similar to those of the previous tier, Figure 4.1.

C. LONG RANGE SAM SHIP DEFENSE (TIER 3)

Long range SAM ship defense is shown in Figure 4.6 and connected to the SR SAM ship defense tier by the T3 connector. The entire complex of events is nearly identical to that for the SR SAM ship system. The problems associated with preventing further penetration of the ASCM are similar in either case, however the fire control solutions are somewhat different. Intercepting the ASCM in its cruise phase represents a problem that is difficult to solve. Further analysis of the cruise phase intercept is outside the scope of this work.

D. CAP DEFENSE (TIER 4)

Although the use of CAP aircraft to prevent penetration of an ASCM after launch is arguable from a practical standpoint, the event is included in the analysis because it represents a low probability extreme. To omit it from the model would be inappropriate. It is connected to the events of Tier 3 (LR SAM Ship Defense) by the "T4" connector. For the

ASCM to penetrate through the CAP defenses it must initially have been launched by the LR Bomber at either a STANDOFF range or a REDUCED standoff range. These events are shown in Figure 4.7. Once launched, it proceeds to high altitude through the interceptors defense. ASCM evasion of the CAP defenses is shown in Figure 4.8. It is joined to Figure 4.7 by the "asm" connector.

Figure 4.8 is symmetrical, LR CAP and MR CAP have similar supporting events, however only the subevents associated with the MR CAP are shown. The connectors "lrc1" and "lrc2" (referring to LR CAP) are used to expand the events that lead to "LR CAP does not fire" shown in Figure 4.9 or to "LR CAP fires AIM at ASCM and misses" shown in Figure 4.10.

E. ASCM LAUNCHED FROM STANDOFF RANGE

Consider the case where the long range bomber has targeting information that will allow launching the ASCM from near maximum range. Figure 4.11 displays the contributing events that lead to ASCM launch at long range. Countertargeting by the battle force has been ineffective and the LR bomber proceeds to launch range while updating the targeting information. The ASCM is then launched and flies to its preassigned destination (carrier) autonomously. The details of the LR bomber evading the LR CAP are imbedded in Figure 4.11. It should be noted that the connectors "fcs" and "nel" support the events of this figure.

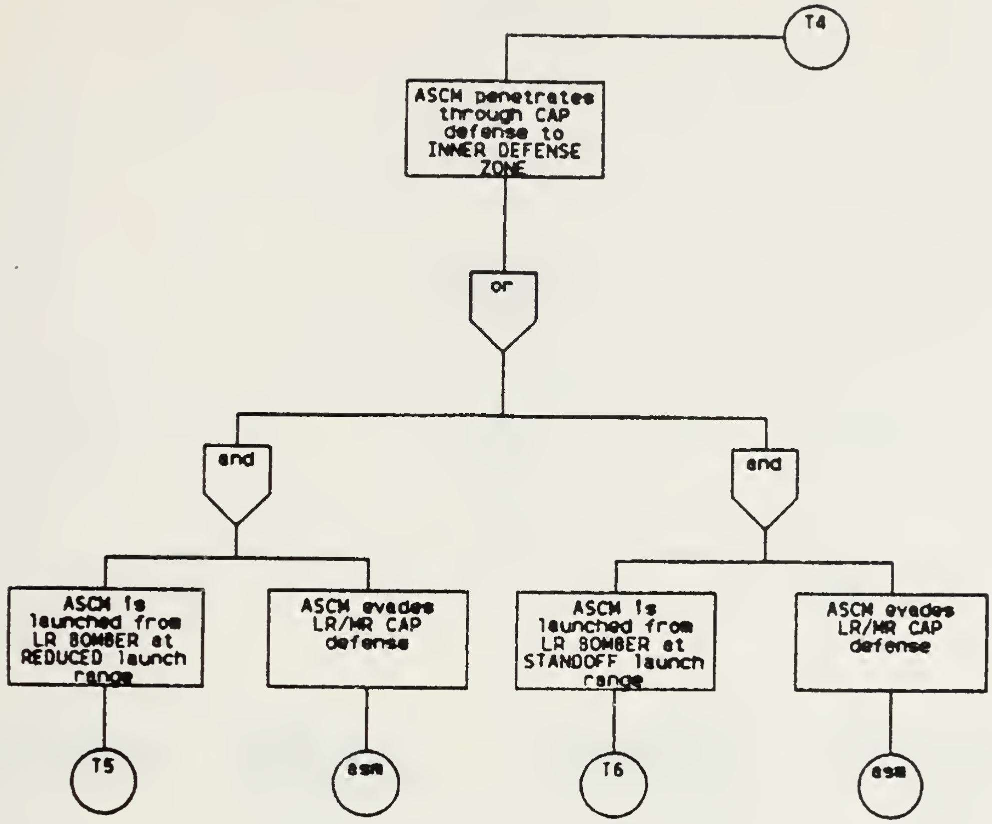


Figure 4.7 ASCM PENETRATES CAP DEFENSE TO INNER DEFENSE ZONE

F. ASCM LAUNCHED FROM REDUCED RANGE

This section deals primarily with the countertargeting problem encountered by the hostile force. As previously postulated, it is the intention of the LR bomber to launch the missile at maximum range consistent with the quality of the targeting solution and the bomber's exposure to battle force interceptors. The events contributing to ASCM launch at REDUCED range are displayed in Figure 4.12. This figure integrates "degrees" of countertargeting into the problem. Countertargeting is initially effective so the LR bomber continues inbound

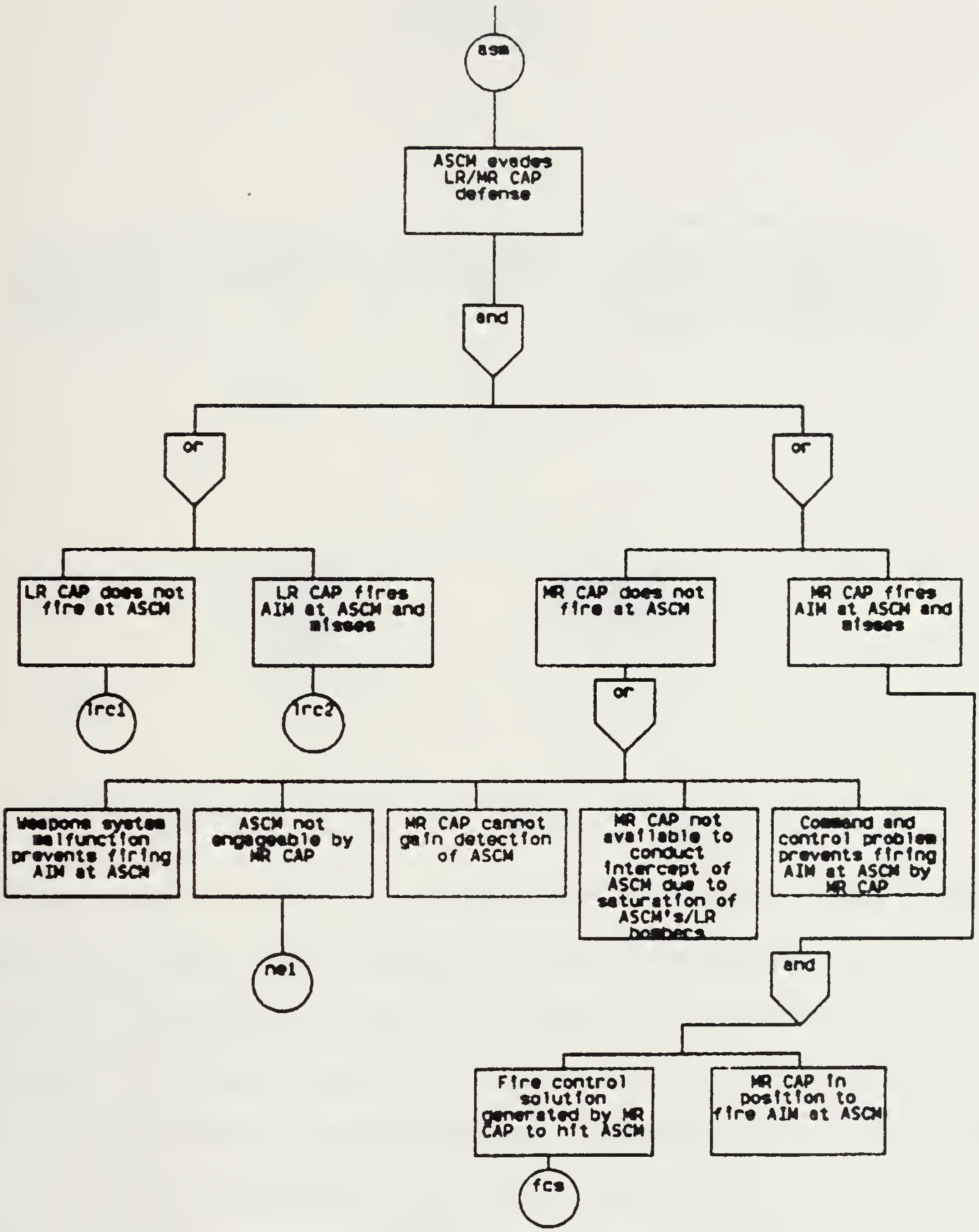


Figure 4.8 ASCM EVADES CAP

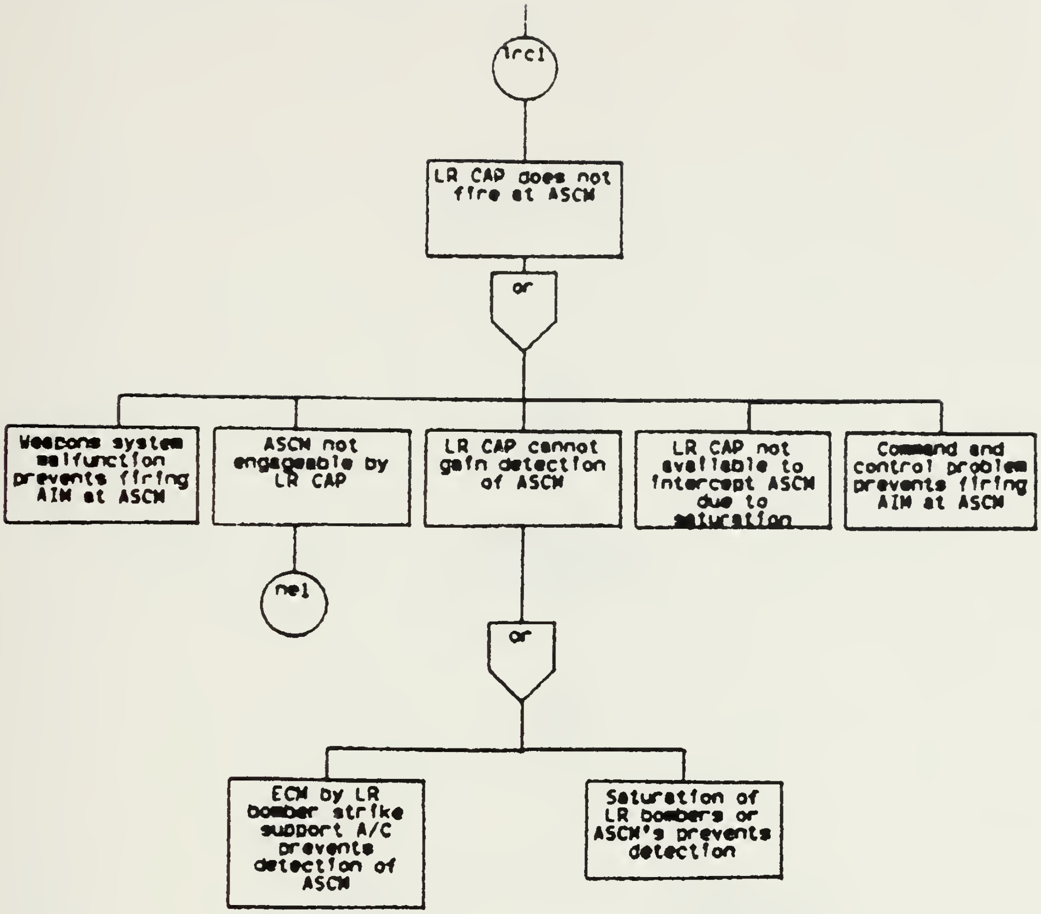


Figure 4.9 LR CAP DOES NOT FIRE AT ASCM

toward the carrier until either the LR bomber gains accurate targeting data (and launches) or the LR bomber encounters resistance with the outer air battle interceptors. Targeting range is not well defined in any case thus the supporting events to "ASCM launch at REDUCED range" are somewhat flexible. The connectors "lrc3" and "lrc4" join the subevents that relate to the firing or nonfiring of AIM's at the LR bomber. Similarly, "mrc1" and "mrc2" refer to medium range CAP events which relate to the firing or nonfiring of MR CAP

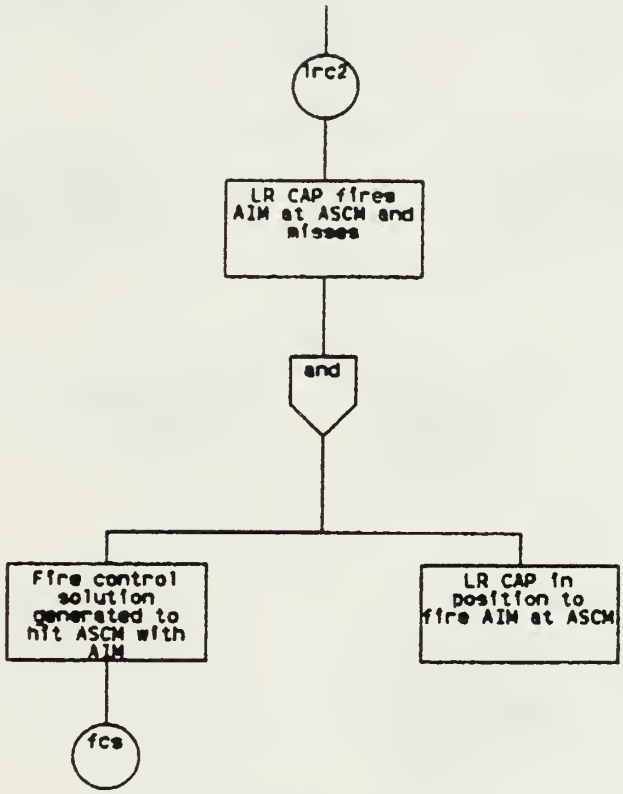


Figure 4.10 LR CAP FIRES AIM AND MISSES ASCM

launched AIM's. The events that detail CAP launched missile firings at the LR bomber are shown in Figures 4.13 through 4.16.

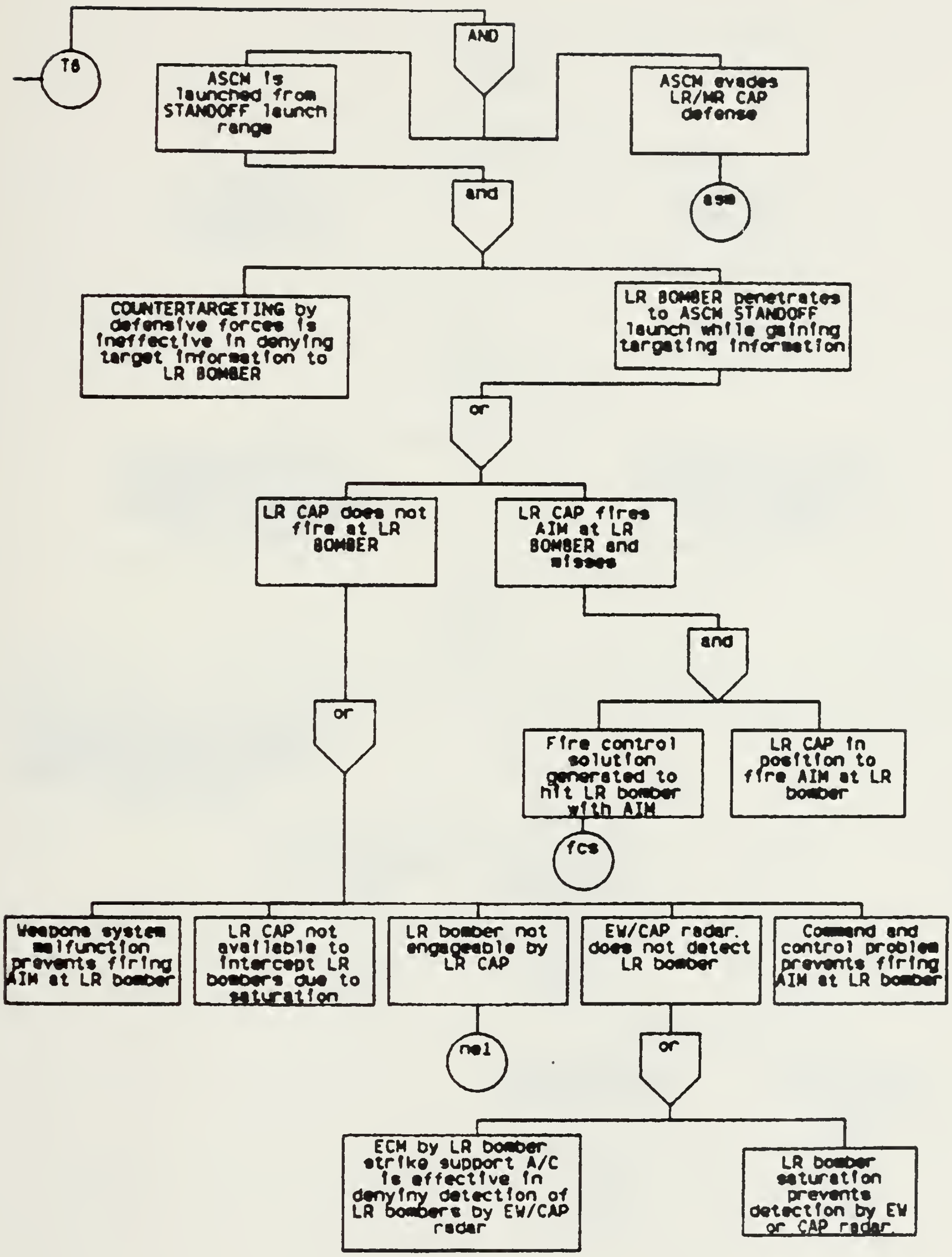


Figure 4.11 ASCM FIRED FROM STANDOFF RANGE

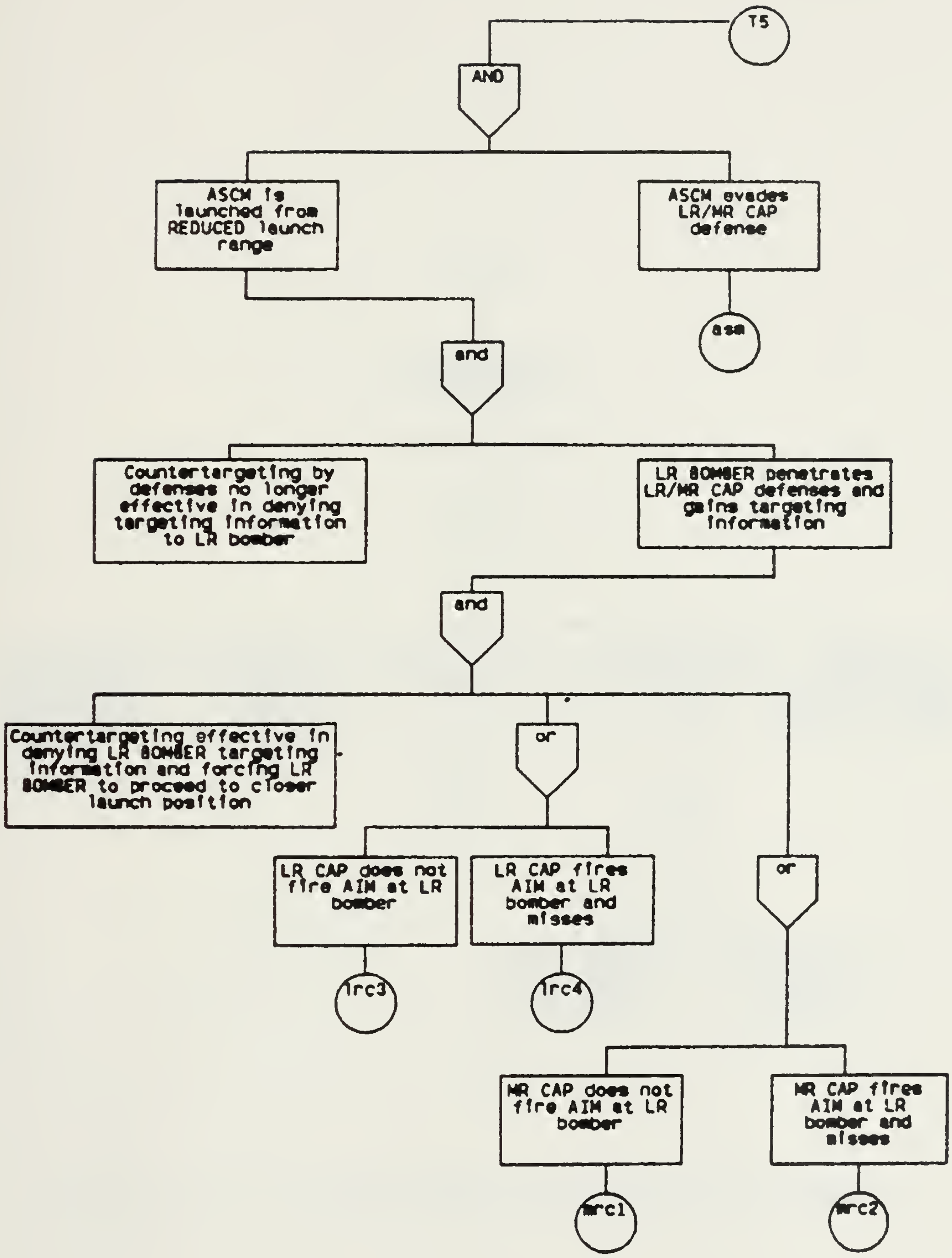


Figure 4.12 ASCM FIRED FROM REDUCED RANGE

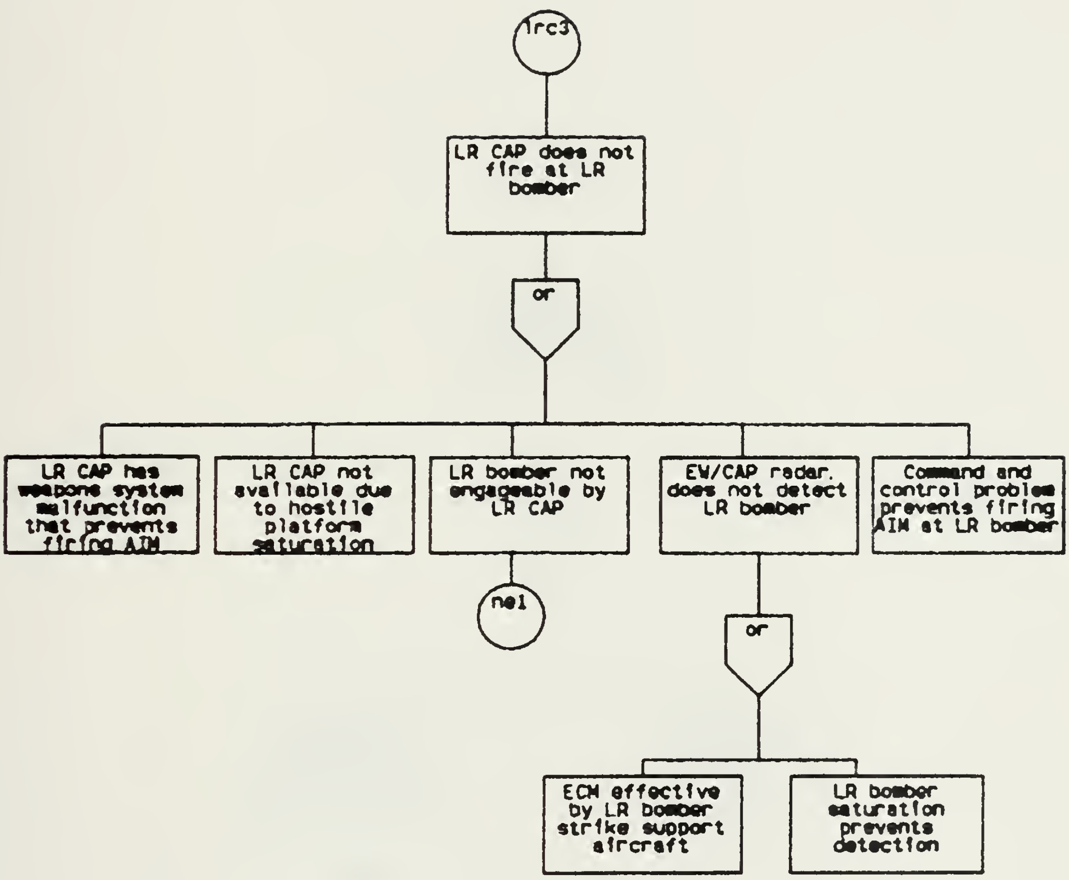


Figure 4.13 LR CAP DOES NOT FIRE AT LR BOMBER

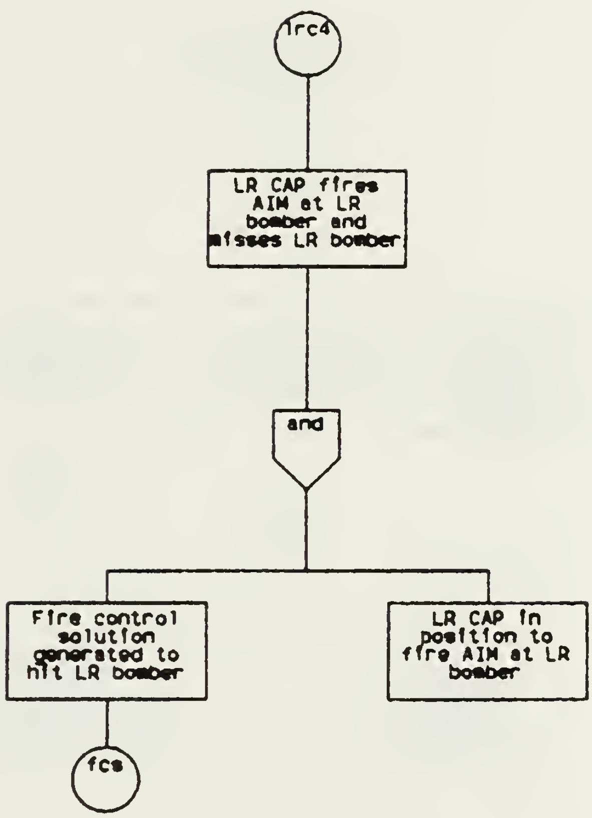


Figure 4.14 LR CAP FIRES AIM AT LR BOMBER

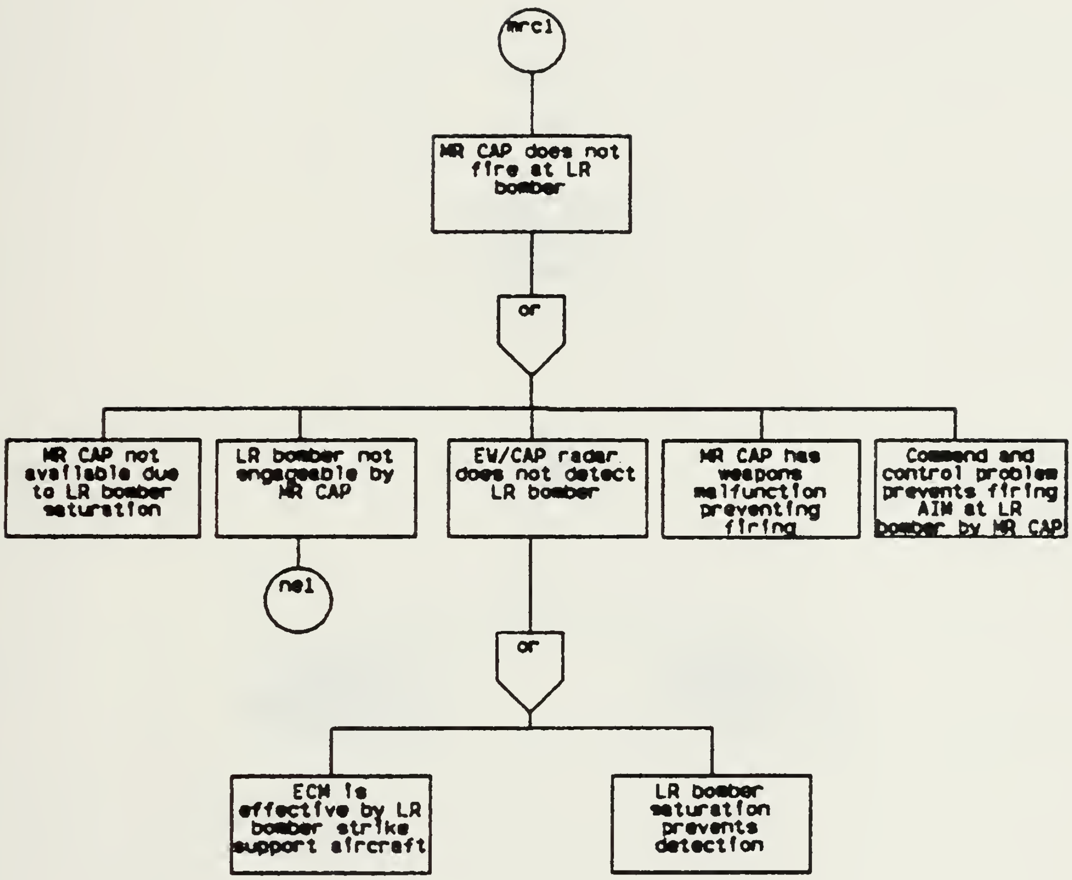


Figure 4.15 MR CAP DOES NOT FIRE AT LR BOMBER

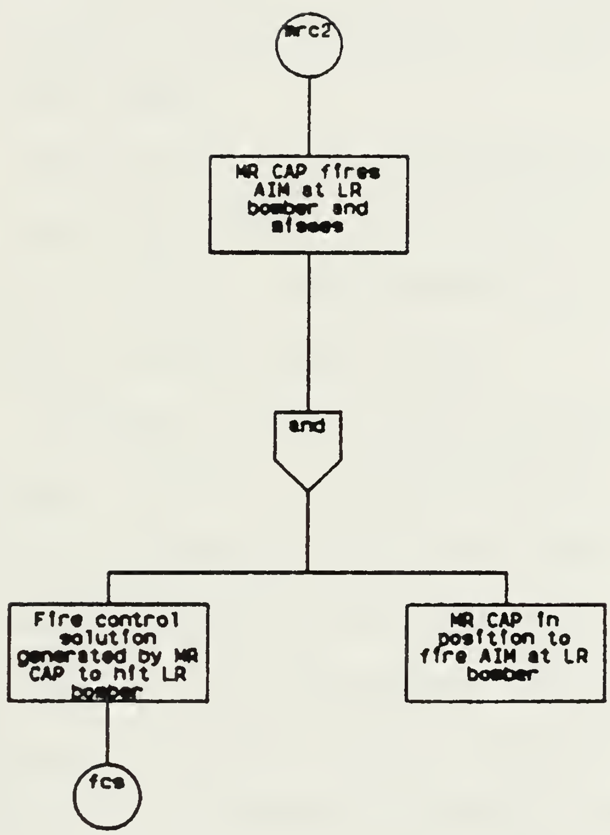


Figure 4.16 MR CAP FIRES AIM AT LR BOMBER

V. USEFULNESS AND CONCLUSIONS

A. QUALITATIVE INSTRUCTIONAL TOOL

At the outset of this work a discussion was initiated on the use of Fault Analysis as a quantitative predictor and a qualitative instructional tool. To illustrate these concepts an AAW scenario was introduced and fault tree analysis was applied to the model.

The model was qualitatively developed using fault tree methodology to describe the flow of logic that is necessary to lead to mission failure. The mission in this case was to defend a carrier against ASM attack.

The model is simple enough to use as an instructional device for primary students in naval warfare. It is robust enough to use as a diagnostic tool when analyzing the tactics that prevent the occurrence of the top event.

The flow chart style of annotation in FTA is compatible with naval warfare scenarios. One of the features of a flow chart presentation is to enable a student client to gain an appreciation for the "big picture". By viewing the AAW scenario from the big picture vantage point it enables the operator at the radar scope level to better understand the objective. This may have the added benefit of yielding more effective and reliable performance.

At the warfare commander level, the client is better able to identify critical combinations of successes (or failures) that can lead to a more efficient allocation of personnel and hardward in either a training or operational environment.

As a visual tool, it can be used for communicating results and supporting decisions that might otherwise seem ambiguous.

This AAW model has identified the "big picture" events that lead to a hit on the carrier. The model admits detailed analysis of the events that enter throughout the model, for example, the event "Command and control problem prevents firing AIM (LR or SR SAM) at ASCM". The "command and control problem" at any stage is one of the more important inhibitors of efficient operations in naval warfare. It is also one of the most difficult to solve. Developing the failure event labeled "Command and control ..." may uncover a solution to the problem not before realized. In addition, a problem not initially recognized as a problem may emerge and coincidentally be solved. Just recognizing the problem and being able to define it sometimes leads to a solution.

Many events throughout the model are undeveloped. One of the features of FTA is that the model is developed top down. Undeveloped events can then be expanded by specialists using relevant experience and technical knowledge. For example, the event in Figure 4.2 "Fire control solution is generated to hit the hostile target" is such an event.

Little emphasis has been placed in the model on the electronic measures conducted by the hostile platform to prevent

detection and destruction before launch of the ASCM. In reality this area receives considerable attention and it is of major importance to both sides. It is an event to which considerable thought and research has been devoted. A specialist in electronic warfare could develop the concepts (events) and provide further insight into the problem.

Finally, by considering the "dual" of the fault tree or the success tree, event tree analysis can be a corroborative aid in operational planning. By developing the events that lead to the event "Carrier is not hit" (the complement of the model's top event) the warfare commander may encounter an aspect of the problem not previously viewed.

B. QUANTITATIVE PREDICTIVE TOOL

The objective of this work was to examine event tree analysis, and more specifically Fault Tree Analysis, when applied to an AAW scenario. The scenario was developed qualitatively. The quantitative aspects of the analysis were not examined. The purpose of this section is to mention the quantitative possibilities in the FTA approach.

Many models have been developed in AAW that use gaming and simulation methodology. Many of these models are used in the instructional environment to enhance a student's tactical ability to use and understand modern platforms and weapons. Imbedded in the games are probabilities (based on assumed distributions) of specific events occurring with the end result

(in this case) that the "Carrier is hit" or the "Carrier is not hit" depending on the tactic used and the final implicit probability.

Proposed from this model is not so much the stochastic result, e.g., "with .05 probability, the carrier is hit" but in a broader sense the sensitivity of that result to various inputs or events. The model as presented is in some respects not usable for such an analysis. Given further embellishment however, it could be a useful tool in sensitivity studies. To help with the problem of where to place additional emphasis to reduce the probabilities associated with the end or intermediate results is certainly an inducement to use it in operational planning.

The issue here is in attempting to assign probabilities that are clearly subjective arguments on the state of the system. Many assumptions must be made to accomplish these assignments, including a problematic one about the independence of events. This would have to be done cautiously in order to preserve the usefulness of the sensitivity study.

An example of how the Initial Scenario proposed in Chapter II, and described graphically in Figure 3.2 might be quantified is given in APPENDIX A. A more detailed analysis is beyond the scope of this work.

C. OTHER SCENARIOS

Other scenarios, analagous to AAW are aptly described by a fault tree or a success tree. Suppose similar scenarios were developed using the same degree of detail that was used in the AAW model. By exposing these trees to the critique of students and warfare commanders, the level of communication and understanding at all echelons could be increased. Below are listed other warfare environments and scenarios that are amenable to analysis using event trees.

1. AAW

- Submarine launched cruise missiles targeted for the carrier.
- Surface launched cruise missiles targeted for the carrier.
- Air-to-Air engagement.
- SAM engagements.

2. Anti-Surface Warfare (ASUW)

- Type engagements involving combat surface vessels.

3. Anti-Submarine Warfare (ASW)

- Submarine versus submarine engagements.
- Submarine versus surface ship engagement.
- Surface ship versus submarine engagement.
- Submarine versus antisubmarine aircraft engagement.

APPENDIX A

PROBABILITY ANALYSIS OF THE INITIAL SCENARIO

A typical probability analysis of the Initial Scenario would proceed along the lines as follows:

P_H = P(Carrier is hit)

= P(Raid penetrates, missile is fired and hits)

= P(Missile is fired and hits/ Raid penetrates) x P(Raid penetrates)

= $P_M \times P_R$

where

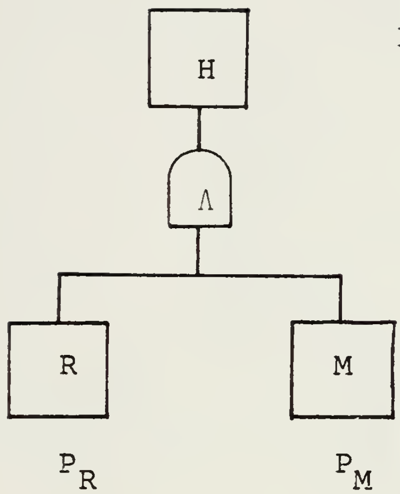
P_M = P(Missile is fired and hits/Raid penetrates) is the conditional probability that the missile succeeds once it is within range

and

P_R = P(Raid penetrates) is the probability that the missile can be brought within range

The fault tree for the Initial Scenario expresses the event H = (Carrier is hit) as the logical "and" of the event R = (Raid penetrates) and M = (Missile is fired and hits).

The event H is the consequence of transmitting the events R and M through the "and" gate. In the same vein, the probability P_H can be viewed as the result of transmitting the probabilities P_R and P_M through the "and" gate.



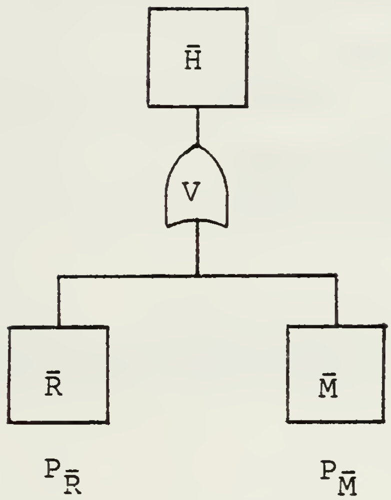
$$P_H = P_R \wedge P_M = P_R \times P_M$$

$$P_1 \wedge P_2 = P_1 \times P_2$$
is the probabilistic "and" of the probabilities P_1 and P_2.

The success tree for the Initial Scenario relates the events $\bar{H}$ = (Carrier is not hit) to the events $\bar{R}$ = (Raid does not penetrate) and $\bar{M}$ = (Missile does not hit). The events $\bar{H}$, $\bar{R}$, $\bar{M}$ are the logical opposites of the events H, R and M.

The event $\bar{H}$ is the consequence of transmitting the events $\bar{R}$ and $\bar{M}$ through the "or" gate. The probability $P_{\bar{H}}$ can be viewed as the result of transmitting $P_{\bar{R}}$ and $P_{\bar{M}}$ through the "or" gate.

It must be emphasized that the probability analysis presented illustrates only the simplest cases. A probability analysis on the AAW scenario medeled in this work will require some more difficult techniques.



$$P_{\bar{H}} = P_{\bar{R}} \vee P_{\bar{M}}$$
$$= P_{\bar{R}} + P_{\bar{M}} - (P_{\bar{R}} \times P_{\bar{M}})$$
$$= 1 - (1 - P_{\bar{R}})\ (1 - P_{\bar{M}})$$

$$P_{\bar{H}} = 1 - P_H$$
$$P_{\bar{R}} = 1 - P_R$$
$$P_{\bar{M}} = 1 - P_M$$

$P_1 \vee P_2 = P_1 + P_2 - (P_1 \times P_2)$

$= 1 - (1 - P_1)\ (1 - P_2)$

is the probabilistic "or" of the probabilities P_1 and P_2.

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